Channel Evolution and Erosion in PAM–Treated and Untreated Experimental Waterways

J. R. Peterson, D. C. Flanagan, K. M. Robinson

Abstract. *Unprotected earthen waterways (e.g., grassed waterways before vegetation) and ephemeral gullies are prone to severe erosion. Previous research has suggested that polyacrylamide (PAM) may reduce erosion in areas of concentrated flow. This research tested the hypothesis that a PAM–treated channel would result in significantly less erosion than untreated soil in a pre–formed, trapezoidal channel measuring 0.6 m at the top, 0.1 m at the bottom, 0.13 m deep, and 15.2 m long. Anionic PAM (30% charge density, 18 Mg mol^{-1} molecular weight) was applied in solution at a rate of 80 kg ha^{-1}. The soil used in these experiments was red clay loam (37% sand, 35% silt, 28% clay). Channel geometry and sediment concentration were measured for each of four inflow rates (0.0016, 0.0032, 0.0063, and 0.0126 m^3 s^{-1}). A secondary objective was to measure the influence of PAM on headcut rate advance. Measured sediment yield rate was significantly less from PAM–treated channels than from the control. Reductions in sediment yield rate ranged from 93% to 98%. Channel incision depth was not different between the two treatments; however, effective flow widths (assuming rectangular channel geometry) were significantly greater for the untreated control channel. Headcut advance rates were greatly reduced in PAM–treated channels (0.06 to 0.6 m h^{-1}) compared to the untreated channel (17.8 m h^{-1}) in our limited data. These results show that PAM was an effective means of controlling erosion in experimental earth channels.*

Keywords. *Channel, Erosion, Gully erosion, Headcut, PAM, Polyacrylamide, Sediment yield.*

Ephemeral gullies are channelized flow areas that are generally formed downslope of rills or a rill network. Ephemeral gully location is primarily determined by the macrorelief of the terrain. Gullies are distinguished from rills by their larger size. Gullies may be eliminated by tillage operations but will otherwise tend to recur in the same location without change to the macrorelief (Haan et al., 1994). Gullies that form on agricultural lands and can be removed by tillage operations are termed ephemeral gullies (Foster, 1986), while those that are permanent are called classic gullies (Harvey et al., 1985). Soil detachment in gullies is caused by the shearing force of flowing water, channel wall failure, and headwall failure (Haan et al., 1994). Bennett et al. (2000) discussed the problem of ephemeral gully erosion at length.

Gully erosion can be a significant problem, yet little research exists on sediment yield rates and the time variation in gully morphology in an actively eroding channel (Bennett et al., 2000). Bennett et al. (2000) noted that there is no unique solution to prevent or mitigate ephemeral gully formation and erosion, although vegetation management programs might be an effective means of controlling gully erosion. However, before vegetation is fully established, a gully or waterway is still susceptible to erosion. Previous research has indicated that polyacrylamide (PAM) may be effective in controlling erosion due to concentrated flow (Flanagan et al., 1997a, 1997b; Peterson et al., 2002b; Flanagan et al., 2002a).

Polyacrylamide is a water–soluble, synthetic organic polymer high in molecular weight that interacts primarily with the clay fraction of soils (Seybold, 1994) and has been proven to be superior to other polymers in erosion control applications (Shainberg and Levy, 1994). Polyacrylamide stabilizes the soil by reducing repulsive forces among clay particles and acts as a bridge between soil particles in an aggregate by bonding with the particles (Ben–Hur, 1994). Anionic PAM has been found to be superior to cationic and nonionic PAMs for erosion control applications (Shainberg and Levy, 1994). Polyacrylamide has been studied extensively for use in furrow irrigation (Lentz and Sojka, 2000; Sojka et al., 1998), sprinkler irrigation (Bjorneberg et al., 2000; Aase et al., 1998), and construction site/disturbed area erosion control (Flanagan et al., 2002a, 2002b; Peterson et al., 2002b). However, the use of PAM to control erosion in a high–volume concentrated flow situation, typical of a gully or waterway, has not been studied.

Flanagan et al. (1997a, 1997b) and Peterson et al. (2002a, 2002b) studied the effectiveness of PAM at controlling erosion and runoff in interrill and rill situations. The field study by Flanagan et al. (1997a) showed no significant effect of a 20 kg ha^{-1} PAM treatment on final interrill and rill runoff or infiltration rates, which was attributed to considerable variability in their experiments. Flanagan et al. (1997a) noted

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that PAM treatments appeared to reduce aggregate breakdown and enhance infiltration rates. No significant differences between PAM–treated and untreated soil were found in terms of interrill sediment concentration or sediment yield rates, but average rill sediment concentration and steady–state sediment discharge were significantly reduced for the PAM treatments in the run on initially dry soil (Flanagan et al., 1997a, 1997b). Peterson et al. (2002a, 2002b) used a clay loam soil in both a plot–scale field experiment and an indoor laboratory setting using a similar rainfall intensity and duration. Both studies were conducted at a 17% slope. Erosion and runoff from PAM treatments were both significantly reduced, compared to untreated soil, and reductions were greater in the rill–dominated field study than in the interrill–dominated laboratory experiment.

The hypothesis being tested is that PAM significantly decreases erosion in a PAM–treated earthen channel, as compared to an untreated earthen channel. Specific objectives were to compare differences in sediment concentration, channel cross–section, and channel profile between the PAM–treated and untreated channels. A secondary objective was to compare the headcut advance rate between treated and untreated channels.

Materials and Methods

Three experiments were conducted at the USDA–ARS Hydraulic Engineering Research Unit in Stillwater, Oklahoma, using a 29 m long, 1.8 m wide, and 2.4 m deep reinforced concrete flume (see Robinson and Hansen, 1996). Soil used in the experiments was a red clay loam (37% sand, 35% silt, 28% clay) stored on site that had been excavated from a borrow pit near Stillwater, Oklahoma. A standard compaction test (ASTM D–698) performed by Robinson and Hanson (1996) indicated a maximum dry density of 1.92 Mg m^{-3} and optimum moisture content of 12.5%. The stockpiled soil was tilled before channel preparation to break down large aggregates, to ensure a more uniform aggregate size in the flume, and to assess and, if necessary, modify the moisture content of the soil.

Our objective was to pack the flume with soil to a depth of 0.8 m at a 1% slope at a bulk density of 1.92 Mg m^{-3} and then to cut side–by–side parallel trapezoidal channels down the length of the flume. Seven to nine layers of soil, approximately 10 cm deep, were placed in the flume to achieve the desired depth. Preparation of each layer proceeded as follows: placement of soil in flume using a skid loader, screeding, compaction, and raking. Stockpiled soil was added to the flume using a skid loader. The soil was evenly spread across the width of the flume and then screeded to a uniform height. The screed was suspended from side rails attached to the flume walls. These angle iron side rails were mounted at a 1% slope. After screeding, the soil was compacted using a remotely controlled compactor measuring 0.86 m wide. The compactor was driven twice over each side of the flume. Soil adjacent to the concrete walls was compacted using a pneumatic tamper. After compaction, the surface of the soil was raked to improve cohesion between layers. To permit equipment access to the soil and to control the water exiting the channels, a ramp leading from the channels to the floor of the flume was constructed by decreasing the length over which the soil was applied in successive layers. Soil samples were taken at random locations from each layer in the bed to assess soil moisture content. After each experiment, the flume was cleaned out and packed with new soil for the next experiment.

Channels were formed by using a specially designed, hydraulically powered tiller. The tiller was attached to the front of a skid–steer loader. The tiller rested on the same rails used to support the screed. This ensured a uniform 1% longitudinal slope. Two parallel channels were cut in the surface of the test bed in one pass with the tiller. Each channel measured 0.6 m wide at the top, 0.1 m wide at the bottom, 0.13 m deep, and 15.2 m long. The edge of each channel was approximately 0.2 m from the wall of the flume, with approximately 0.2 m separating the channels. All loose soil displaced by the tiller was removed prior to experimentation. A carriage suspended from rails on the top of the flume walls allowed access to the soil surface with minimal contact to the test bed.

Variation in bed morphology and sediment concentration with time was measured for each of four inflow rates (0.0016, 0.0032, 0.0063, and 0.0126 m^3 s^{-1}), increased sequentially for a given experiment. Inflow was stopped between flow rates in order to record measurements, which typically lasted one–half hour. In some cases, a fifth testing period was conducted depending on channel status at the end of the first four flow rates to: (1) determine whether the lack of failure observed in PAM–treated channels during the relatively short duration tests (tests A through D) would be observed over a longer duration, and (2) study the effect of PAM on headcut advance rate. This additional testing was conducted on all three PAM–treated channels but on only one of the untreated control channels. Sufficient erosion had occurred in two of the untreated channels such that further testing was not practical. Headcut advance was measured by introducing a knickpoint in the channel bed at the downstream end of the channel. Knickpoints were made at the downstream end of the channel just before the channel outlet ramp. The knickpoints were 7.5 cm deep, 22.5 cm wide, and approximately 1 m long. Headcut advance rate was measured in experiments 1, 2, and 3 for the PAM treatment and in experiment 1 for the control.

A rail–mounted carriage above the test channels was used to measure centerline longitudinal channel elevation, centerline water elevation, and cross–sectional elevation. Longitudinal and cross–sectional channel elevations were measured before and after each flow rate period. Water surface elevation was measured during each flow event. An attempt was made to take these measurements at the beginning of each flow period, especially on the untreated channel. The cross–sectional measurements were taken at 3, 6, 9, and 12 m from the point of inflow and will be referred to as STA 3, 6, 9, and 12.

Two treatments, PAM and a control, were used in this study. Each treatment was replicated three times, with control and PAM treatments being run concurrently. The PAM used in this study was anionic Magnafloc 156 (Ciba Specialty Chemicals Corporation, Suffolk, Va.) having approximately 30% charge density and molecular weight of 17 to 19 Mg mol^{-1}. The PAM was applied once before each experiment at a rate of 80 kg ha^{-1} at a concentration of 1000 ppm using a sprayer and a roller pump powered by a 2.2 kW motor. The PAM was applied to the soil surface one day before the experiment to enhance PAM efficacy (Peterson et al., 2002b).

Cross–sectional and water surface elevation data were used to estimate area of flow, wetted perimeter, and average bed shear stress. Cross–sectional data were taken at four different locations on both channels (treated and untreated). Flow area at these locations was determined by integrating the differences between the water surface elevation and bed elevation. Average flow area was computed using cross–section data collected before and after each flow period. Wetted perimeter was estimated by averaging the before and after wetted perimeter obtained from the cross–section data. Average bed shear stress for each test was computed as the average of the shear stress at each station where cross–sectional data were collected before and after an inflow event.

Sediment concentration was measured by collecting replicate 1 L samples at three different times, generally spaced evenly across the second half of each flow duration. Sediment concentration samples were weighed, flocculated with alum, decanted, oven dried at 105°C, and weighed again. Measured sediment yield rate for each test was computed by averaging the six sediment concentration samples and multiplying by the flow rate for that test. Calculated sediment yield was computed by integrating the difference in cross–sectional elevation across the width of the channel, multiplying by the measured bulk density, and multiplying by the representative length of the channel. Differences in sediment yield rate, effective flow width, and flow depth between treatments were determined using Tukey's multiple comparison test with $\alpha = 0.05$ (Neter et al., 1996).

Results and Discussion

Initial Conditions

Maximum dry density of this soil was determined to be 1.92 Mg m^{-3} at a moisture content of 12.5% (Robinson and Hanson, 1996). In–place soil conditions from the three experiments are listed in table 1. Average moisture content, ranging from 8.1% to 9.8%, for all three experiments was below the targeted value. Consequently, in–place dry density of the soil ranged from 85% to 90% of the maximum.

Table 1. Average moisture content and in–place dry bulk density for each experiment (numbers in parentheses indicate number of samples used to compute the average).

Experiment	Average Moisture Content Mass Basis (%)	Pre–test Bulk Density (Mg m^{-3})	Post–test Bulk Density (Mg m^{-3})	Pre–test Percent of Maximum (%)
1	8.1 (8)	1.73 (2)	1.68 (3)	90
2	9.3 (9)	1.64 (2)	1.65 (4)	85
3	9.8 (9)	1.70 (2)	1.68 (4)	89

Tests A through D

In the following discussion, the experiments are labeled by the experiment number and the flow rate (for example, Test 1B represents experiment 1 for the second flow period). Flow characteristics from the experiments are presented in tables 2 and 3. Both flow depth (column 5) and effective channel width (column 8) increased with successive flow rates for the treated and untreated channels. Flow depths were generally less for the untreated channel than for the treated channel. However, effective flow widths, assuming a rectangular cross–section, were significantly greater for the untreated channel in all tests for all four flow rates ($\alpha = 0.05$). In the treated channel, there was little erosion; therefore, as the flow rate was increased, the flow depth became greater. In the untreated channels, the bulk of the erosion appeared to occur from the sides of the channel. Thus, the channel became wider, and the corresponding change in flow depth with successively greater flow rates was not as great as that exhibited by the treated channel. Table 2 indicates that the average channel cut depth for the PAM–treated channels was negligible, with the average cut during an experiment ranging from –2 mm to 1 mm. A negative number indicates deposition. Surprisingly, average channel cuts for the untreated channels were typically negative numbers, indicating net deposition along the length of the channel. There were no significant differences in channel cut between treated and untreated channels.

Table 2. Average flow and channel characteristics for PAM–treated channels.

Exp.	Test	Discharge (m^3 s^{-1})	Test Duration (h:min)	Flow Depth (m)	Hydraulic Radius (m)	Average Flow Area (m^2)	Average Flow Width (m)	Average Channel Cut (m)	Flow Velocity (m s^{-1})	Water Surface Slope (m m^{-1})	Bed Slope (m m^{-1})	Bed Shear Stress (Pa)
1	A	0.0016	0:30	0.0254	0.0160	0.0036	0.141	0.000	0.46	0.0100	0.0100	1.57
	B	0.0032	0:30	0.0348	0.0221	0.0056	0.160	0.001	0.58	0.0100	0.0099	2.16
	C	0.0063	0:32	0.0458	0.0281	0.0084	0.184	0.000	0.75	0.0104	0.0099	2.85
	D	0.0126	0:12	0.0635	0.0369	0.0139	0.218	0.000	0.91	0.0104	0.0099	3.76
	E	0.0032	16:22	0.1198	0.0539	0.0605	0.288	0.024	0.31	0.0126	0.0144	6.67
2	A	0.0016	0:33	0.0202	0.0131	0.0025	0.122	–0.001	0.65	0.0099	0.0100	1.27
	B	0.0032	0:30	0.0310	0.0197	0.0049	0.157	0.000	0.66	0.0099	0.0101	1.90
	C	0.0063	0:30	0.0598	0.0346	0.0132	0.218	0.000	0.50	0.0085	0.0101	2.87
	D	0.0126	0:18	0.0610	0.0353	0.0132	0.216	0.001	0.96	0.0106	0.0101	3.69
	E	0.0063	18:40	NA	NA	NA	NA	0.275	NA	NA	0.0177	NA
3	A	0.0016	0:31	0.0256	0.0161	0.0035	0.138	–0.002	0.46	0.0096	0.0100	1.52
	B	0.0032	0:30	0.0323	0.0201	0.0049	0.150	0.001	0.66	0.0096	0.0100	1.88
	C	0.0063	0:29	0.0480	0.0286	0.0091	0.189	0.001	0.70	0.0096	0.0099	2.67
	D	0.0126	0:20	0.0670	0.0387	0.0153	0.228	0.000	0.83	0.0100	0.0101	3.80
	E	0.0063	16:56	NA	NA	NA	NA	0.134	NA	NA	0.0260	NA

NA = not available.

Table 3. Average flow and channel characteristics for untreated channels.

Exp.	Test	Discharge ($m^3 s^{-1}$)	Test Duration (h:min)	Flow Depth (m)	Hydraulic Radius (m)	Average Flow Area (m^2)	Average Flow Width (m)	Average Channel Cut (m)	Flow Velocity ($m s^{-1}$)	Water Surface Slope ($m m^{-1}$)	Bed Slope ($m m^{-1}$)	Bed Shear Stress (Pa)
1	A	0.0016	0:30	0.0268	0.0176	0.0043	0.161	–0.007	0.37	0.0099	0.0093	1.70
	B	0.0032	0:30	0.0283	0.0215	0.0069	0.246	–0.007	0.46	0.0088	0.0074	1.86
	C	0.0063	0:32	0.0348	0.0277	0.0123	0.359	–0.005	0.51	0.0086	0.0062	2.34
	D	0.0126	0:12	0.0443	0.0368	0.0221	0.503	–0.012	0.57	0.0078	0.0048	2.81
	E	0.0063	0:30	NA	NA	NA	NA	0.104	NA	NA	0.0157	NA
2	A	0.0016	0:33	0.0236	0.0170	0.0043	0.178	–0.012	0.40	0.0087	0.0088	1.44
	B	0.0032	0:30	0.0273	0.0232	0.0082	0.303	–0.003	0.38	0.0082	0.0074	1.85
	C	0.0063	0:30	0.0273	0.0218	0.0101	0.370	0.008	0.65	0.0102	0.0089	2.19
	D	0.0126	0:18	0.0475	0.0375	0.0232	0.492	0.014	0.55	0.0117	0.0106	4.28
3	A	0.0016	0:31	0.0238	0.0169	0.0042	0.177	–0.014	0.38	0.0087	0.0090	1.44
	B	0.0032	0:30	0.0275	0.0238	0.0081	0.296	0.000	0.39	0.0079	0.0077	1.83
	C	0.0063	0:29	0.0385	0.0318	0.0130	0.338	0.001	0.50	0.0081	0.0073	2.51
	D	0.0126	0:20	0.0558	0.0441	0.0243	0.438	–0.007	0.52	0.0076	0.0063	3.26

NA = not available.

Figures 1 and 2 show channel cross–sections for the untreated and treated channels, respectively, taken at four different locations along the length of the channel. Cross–section elevations from successive flow rates are superimposed on each figure. Channel incision generally occurred before the first cross–section measurement (fig. 3b). As shown in figures 1a and 1b, there were only slight changes in channel bed elevation. However, further down the channel (STA 9 and 12), deposition tended to increase the channel bed elevation. Computations of net soil lost at these locations generally indicated a net soil gain, or deposition. This indicates that the bulk of the soil lost from the bed in these flow events occurred in the upper half of the channel. This is indicative of a transport–limited flow regime. Figure 2, from the first replication of the PAM treatment, indicates that there was virtually no change in cross–section between flow rates at the four different locations. An apparent change shown in figure 2d for the pre–test cross–section is probably a measurement error. In the untreated channel, changes in channel cross–section are readily apparent. In general, deposition occurred at each of the measured cross–sections, elevating the channel bed. At the same time, channel width increased. Evidence of this is presented in figure 3, which shows longitudinal bed elevation along the channel. As shown in figure 3, the bulk of the erosion in the vertical direction took place in the first 1 to 2 m of the channel. It can also be seen in figure 3b that beyond this scour hole, the centerline channel elevation increased through deposition.

Polyacrylamide treatment was very effective at reducing erosion. Reductions in average sediment yield rate compared to the control channel ranged from 93% to 98% using the sediment sample data. In each flow rate tested, average measured sediment yield rate from the treated channel was significantly less than from the untreated channel ($\alpha = 0.05$) (tables 4 and 5). Figures 4 and 5 are photographs showing the flume during the experiments, and particularly the large effect of the PAM treatment on reducing sediment loss and channel scouring (fig. 5).

Sediment yield rate was also calculated using the cross–section data. However, as discussed previously, the bulk of the erosion in the channel occurred in the first 2 m of the channel, for which there were no data collected. As a consequence, calculated sediment yield rates using this

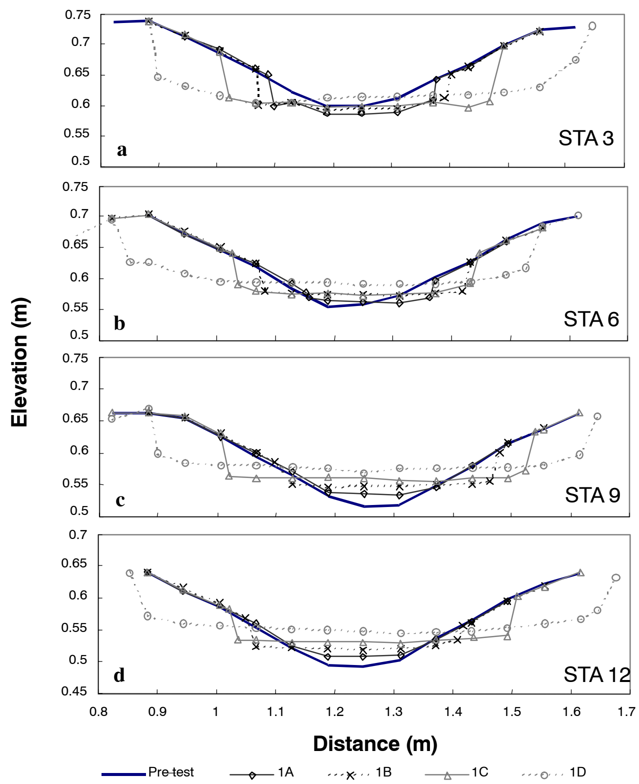

Figure 1. Channel cross–sections before experiment 1 on untreated channel and after successive inflow rates at four different locations along the length of the channel.

method were in some cases negative, representing deposition. The quality of the calculated sediment yield rate using the cross–section data was affected by the amount of erosion that took place. For greater discharges, especially on the untreated channels, calculated sediment yield rate and measured sediment yield rate using grab samples were in fairly good agreement. However, in cases where the change in area was minimal (i.e., low flow rates and PAM–treated channels), the calculated sediment yield values are suspect because the error in calculating the sediment yield was, presumably, of the same magnitude as the sediment yield itself. The slope of the best–fit line between measured and

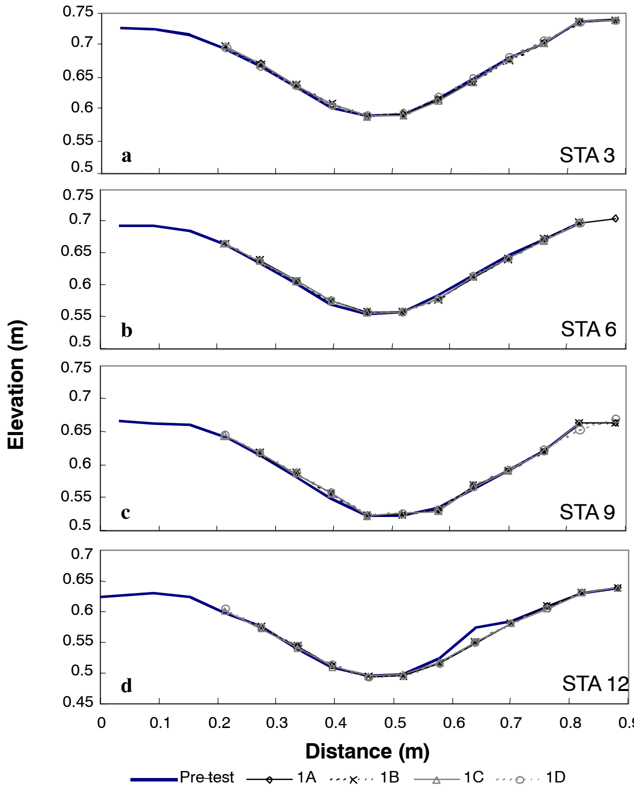

Figure 2. Channel cross–sections before experiment one on PAM–treated channel and after successive inflow rates at four different locations along the length of the channel.

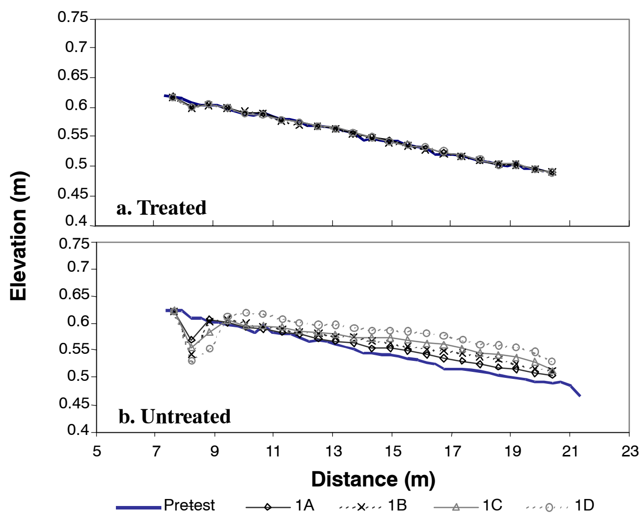

Figure 3. Longitudinal channel bed profiles before testing and subsequent to the first four inflow rates on experiment one.

calculated sediment yield was 0.96, with an r^2 of 0.83 for the untreated (control) data. This suggests that comparisons between measured and calculated erosion rates are well correlated, especially at greater flow rates (>0.0032 $m^3\ s^{-1}$).

In–place soil density in this series of experiments was nearly 90% of maximum (table 1) and therefore may not represent conditions existing in an actual channel, where soil dry density may be less. As PAM used in this context is viewed as a temporary erosion control measure, before establishment of vegetation, it is important to know whether the presence of PAM hinders vegetative growth. Research

Table 4. Measured and calculated sediment yield rates on the PAM–treated channels.

Exp.	Test	Discharge ($m^3\ s^{-1}$)	Measured Sediment Yield Rate (kg min^{-1})	Calculated Average Change in Area (m^2)	Calculated Sediment Yield Rate (kg min^{-1})	Headcut Advance Rate (m h^{-1})
1	A	0.0016	0.03	0.000	0.04	
	B	0.0032	0.03	0.000	0.03	
	C	0.0063	0.09	0.000	0.02	
	D	0.0126	0.17	–0.001	–2.07	
	E	0.0032	—	0.024	0.64	0.06
2	A	0.0016	0.02	0.000	–0.26	
	B	0.0032	0.07	0.000	–0.03	
	C	0.0063	0.16	0.000	–0.12	
	D	0.0126	2.28	0.000	–0.15	
	E	0.0063	—	0.276	6.15	0.6
3	A	0.0016	0.02	–0.001	–0.60	
	B	0.0032	0.04	0.000	–0.05	
	C	0.0063	0.13	0.000	0.36	
	D	0.0126	0.17	0.000	–0.09	
	E	0.0063	—	0.204	5.18	0.4

Table 5. Measured and calculated sediment yield rates on the untreated channels.

Exp.	Test	Discharge ($m^3\ s^{-1}$)	Measured Sediment Yield Rate (kg min^{-1})	Calculated Average Change in Area (m^2)	Calculated Sediment Yield Rate (kg min^{-1})	Headcut Advance Rate (m h^{-1})
1	A	0.0016	0.62	0.001	0.50	
	B	0.0032	1.73	0.000	–0.29	
	C	0.0063	3.15	0.005	4.01	
	D	0.0126	5.79	0.005	10.32	
	E	0.0063	—	0.072	63.44	17.8
2	A	0.0016	0.88	–0.001	–0.55	
	B	0.0032	2.17	0.002	1.57	
	C	0.0063	7.64	0.008	6.63	
	D	0.0126	20.32	0.015	20.67	
3	A	0.0016	0.89	0.000	–0.37	
	B	0.0032	2.60	0.001	0.94	
	C	0.0063	4.96	0.004	3.26	
	D	0.0126	12.20	0.004	5.72	

conducted by Cook and Nelson (1986) and Flanagan et al. (2002b) has indicated that PAM enhances seedling emergence and vegetation establishment.

Headcut Tests

The rate of headcut advance was measured to be 0.06, 0.6, and 0.4 m h^{-1} for tests 1E, 2E, and 3E on the PAM–treated channels and 17.8 m h^{-1} for the untreated channel. Flow discharge during the headcut measurements on test 1E was 0.0032 $m^3\ s^{-1}$ (50 gpm), while discharge during tests 2E and 3E was 0.0063 $m^3\ s^{-1}$ (100 gpm). Flow discharge during the test on the untreated channel was 0.0063 $m^3\ s^{-1}$. Robinson and Hanson (1996) used a similar testing protocol to measure headcut advance for the same soil and found no clear relationship between advance rate and discharge. Our limited data suggest a positive relationship between advance rate and discharge, but statistical certainty cannot be ensured with this limited dataset. Robinson and Hanson (1996) found that headcut advance rate was strongly dependent on initial

Figure 4. Photograph of test bed, looking from inflow point, during experiment 3. The PAM–treated channel is on the left, and the control channel is on the right.

Figure 5. Photographs taken from downstream end of the flume comparing PAM–treated and untreated channels during experiment 3.

moisture content and the dry density of the packed material. Measured advance rates by Robinson and Hanson (1996) ranged from 0 to approximately 18.5 m h^{-1}, although advance rates in most tests ranged from 0.5 to 1.5 m h^{-1}. Average soil moisture content for test 1E in this study was 8.1% (table 1). This value is well below the 12% optimum moisture content that Robinson and Hanson (1996) report. Thus, the relatively rapid advance rate on the untreated channel, compared to data from Robinson and Hanson (1996), is not surprising. Average soil moisture contents in tests 1E, 2E, and 3E were 8.1%, 9.3%, and 9.8%, respectively. The failure of the PAM–treated headcuts was similar to that described by Robinson and Hanson (1996) for their tests with greater moisture contents. In those tests, failure occurred due to tension cracking and larger mass failure events. We observed this mode of failure in the PAM–treated channels. In general,

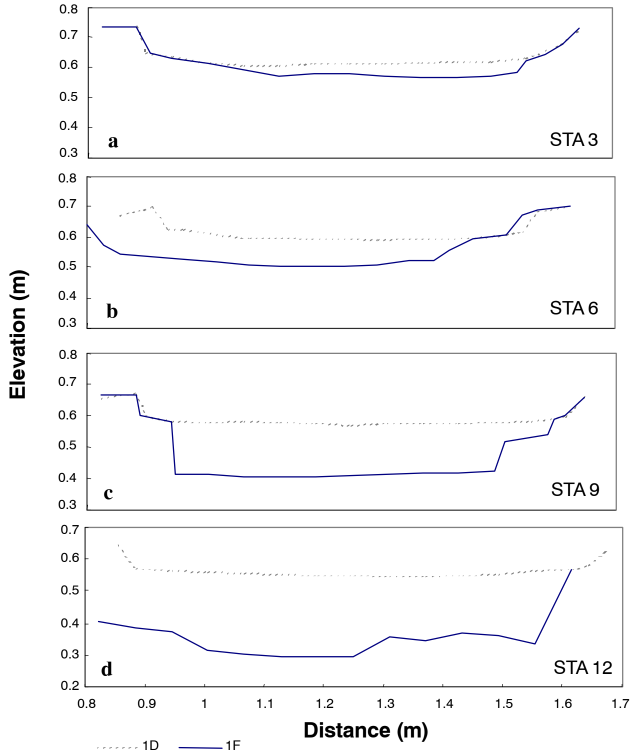

Figure 6. Channel cross–sections before and after 0.0063 m^3 s^{-1} flow rate on untreated channel with knickpoint.

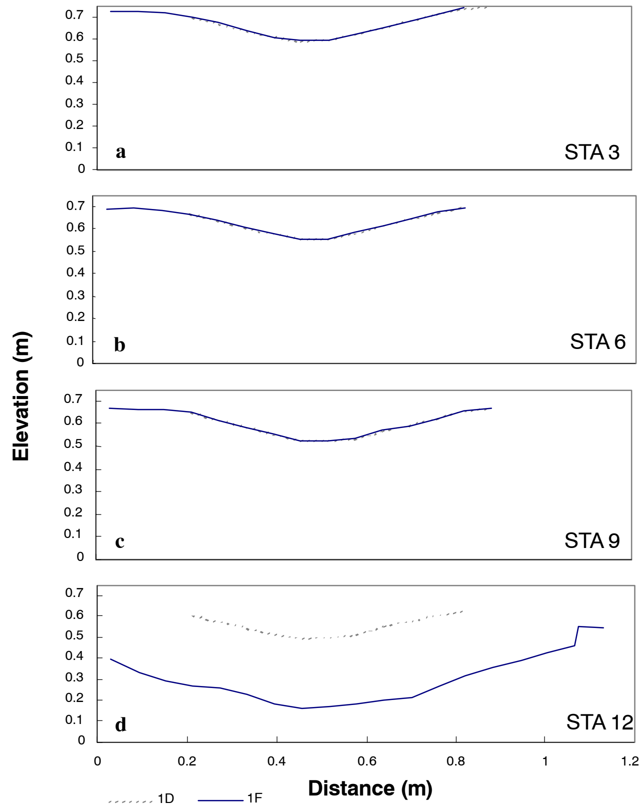

Figure 7. Channel cross–sections before and after 0.0032 m^3 s^{-1} flow rate on PAM–treated channel with knickpoint.

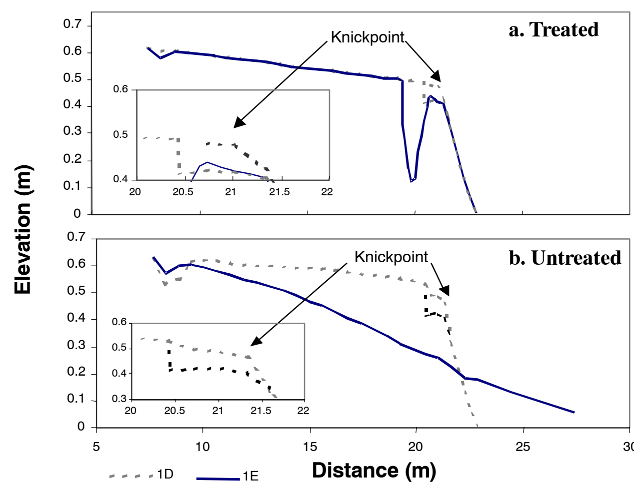

Figure 8. Channel bed profile before and after headcut testing on experiment 1. Inset depicts the channel profile before and after the knickpoint was introduced.

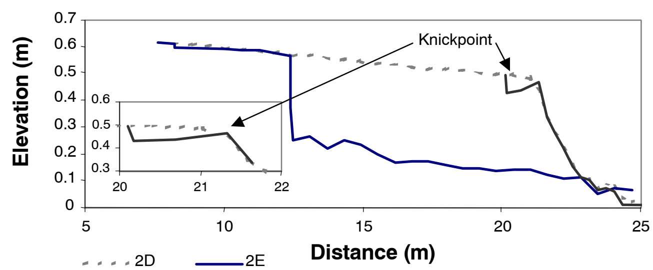

Figure 9. Channel bed profile before and after headcut testing on experiment 2 on PAM–treated channel. Inset depicts the channel profile before and after the knickpoint was introduced.

the backwater below the overfall eroded material from the base of the headcut. As more material was eroded, a visible tension crack developed in the channel, after which a mass failure occurred. It is reasonable to infer that the difference in headcut rate advance between treated and untreated channels observed in this study may be due to a difference in soil strength in the surface material. More testing is required to verify this.

In tests A through D, a plastic sheet was placed at the end of the 1% channel over the outlet ramp. In test E, the plastic was removed, allowing the channel outlet ramp to scour, which greatly affected the controlling water elevation at the outlet. This effect is demonstrated in figures 6 and 7. These figures show channel cross–sections for the untreated and treated channel, respectively, in experiment 1 before and after test E. The corresponding bed profiles from those tests are shown in figure 8. Test E on the untreated channel was performed at a flow rate of 0.0063 m^3 s^{-1} (100 gpm) for a duration of 30 min. Calculated sediment yield rate from this test was 63.4 kg min^{-1}. Other tests on the untreated channel conducted at the same flow rate and for similar duration produced calculated sediment yield rates ranging from 3.26 to 6.63 kg min^{-1}. Channel cross–section was not changed at stations 3, 6, and 9 in the PAM–treated channel after more than 16 h of flow (fig. 7). The headcut advanced beyond station 12, and the channel experienced both widening and deepening (fig. 7d). In contrast to the PAM–treated channels, where the headcut was nearly vertical and appeared to fail through tension cracking and mass failure (fig. 8a), the knickpoint introduced in the untreated channel was not observable at the end of the test. Stress detachment along the channel and over the headcut itself obliterated the headcut, and the lack of a controlling water elevation caused the slope

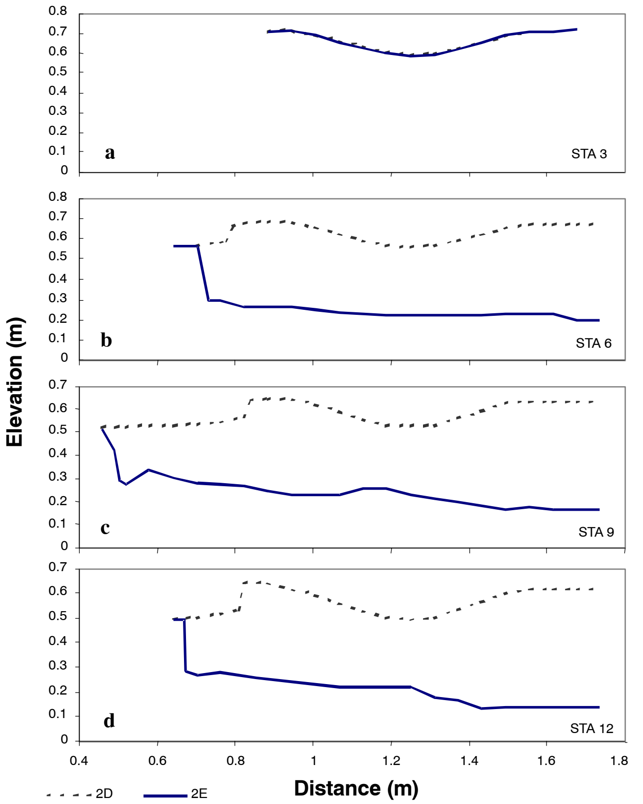

Figure 10. Channel cross–sections before and after 0.0063 m^3 s^{-1} flow rate on PAM–treated channel. Unbounded channel on the right side of figures 10b, 10c, and 10d is location of flume wall.

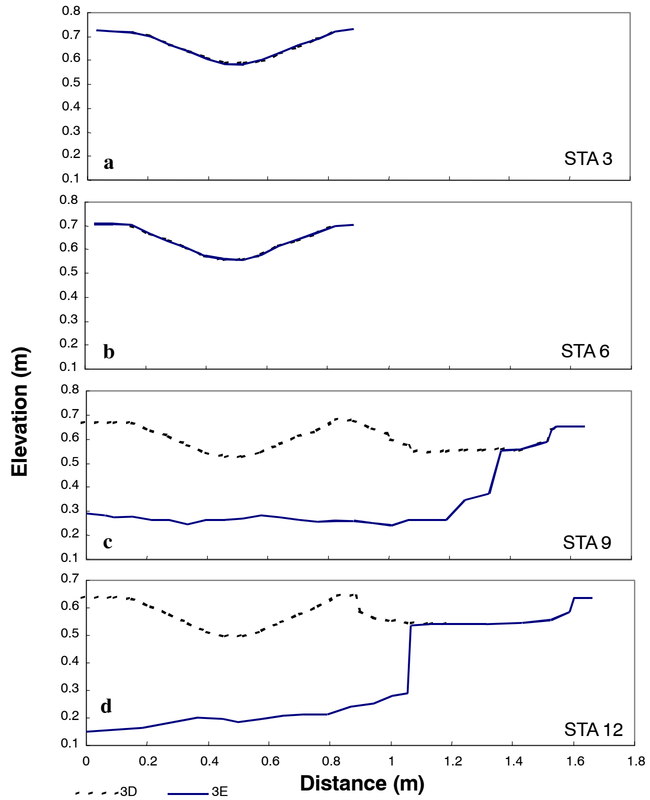

Figure 11. Channel cross–sections before and after 0.0063 m^3 s^{-1} flow rate on PAM–treated channel. Unbounded channel on the left side of figures 11c and 11d is location of flume wall.

of the channel to be uniform from the channel inlet to the concrete floor of the flume (fig. 8b). The headcut in the untreated channel can be clearly seen in figure 8a. The ramp leading from the channel to the flume bottom had also been treated with PAM. Little or no erosion occurred on the ramp, which exhibited greater potential for erosion than the main channel. The calculated erosion rate from this test was 0.64 kg min^{-1}, which is well below the measured sediment yield rate, which ranged from 1.73 to 2.60 kg min^{-1}, from the untreated channel under the same discharge.

Headcut tests on treated channels in experiments 2 and 3 were conducted at 0.0063 m^3 s^{-1} and ran for 18:40 and 16:56 (h:min) durations, respectively. The same mode of headcut failure was observed in 2E (fig. 9) and 3E as in 1E, but the rate of headcut advance was more rapid, and calculated erosion rates were much greater. Calculated sediment yield rates in 2E and 3E were 6.15 and 5.18 kg min^{-1}, respectively. This lies in the range of calculated sediment yield rates from the untreated channel for the same flow rate during test C but is still an order of magnitude less than the calculated sediment yield rate during test E (63.44 kg min^{-1}) on the untreated channel. Channel cross–sections are shown in figure 10 for test 2E. The upstream section of the channel (STA 3) was unchanged after more than 18 h of flow. Cross–sections at stations 6, 9, and 12 experienced considerable erosion because of the headcut advance. At these sections, the channel had eroded into the adjoining channel. The channel was bounded on the right side by the concrete wall of the flume. Similarly, in test 3E (fig. 11), the upper portion of the channel was unchanged during the 17 h discharge period, while the lower portion was eroded considerably.

The cost of PAM compared to more commonly used erosion control practices is an important aspect. The cost of some of these materials in comparison to PAM is presented in table 6. These costs do not account for additional equipment, material, or labor. The cost of PAM, applied at 80 kg ha^{-1}, is much less than any of the other erosion control materials. Woven jute mat and a single–net straw mat were both priced at \$0.38 m^{-2}, while the cost of PAM was estimated to be \$0.07 m^{-2}. This cost comparison shows that PAM is relatively inexpensive and may potentially be used in conjunction with another erosion control method, such as jute mat, and still be a lower–cost alternative to a more expensive product such as coconut blanket. Again, additional equip–

Table 6. Cost comparison between PAM and other erosion control materials.

Product	Cost m^{-2} [a]
Woven jute mat – jute mat	\$0.38
Straw mat – single net	\$0.38
Straw mat – double net	\$0.46
Excelsior mat – single net	\$0.42
Excelsior mat – double net	\$0.50
Stitched coconut blanket – synthetic net	\$0.84
Stitched coconut blanket – organic net	\$1.09
400 g m^{-2} woven bristle coir mat	\$1.00
700 g m^{-2} woven bristle coir mat	\$1.59
900 g m^{-2} woven bristle coir mat	\$2.01
PAM (80 kg ha^{-1})	\$0.07

[a] Price denoted is for material only. Prices listed for material other than PAM are from one supplier and were current as of 4 December 2002. The price of PAM was supplied by Ciba Specialty Chemicals (Suffolk, Va.) and reflects a price that might be obtained from a distributor.

ment, material (e.g., stakes, etc.), and labor should be taken into consideration.

Summary and Conclusions

Testing was conducted to determine the extent to which polyacrylamide (PAM) could reduce erosion, compared to untreated soil, in a pre–formed, trapezoidal channel. Variation of bed morphology and sediment concentration over time was measured for each of four inflow rates (0.0016, 0.0032, 0.0063, and 0.0126 $m^3 s^{-1}$) in three separate experiments. Another testing period conducted at the end of the first four discharges examined the influence of PAM on headcut advance rate.

Measured sediment yield rate was significantly less from PAM–treated channels than from the control. Reductions in sediment yield rate ranged from 93% to 98%. There were no significant differences in channel incision depth, but effective flow widths (assuming rectangular channel geometry) were significantly greater for the untreated control channel.

Headcut advance rates were greatly reduced in the PAM–treated channels (0.06 to 0.6 m h^{-1}) compared to the untreated channel (17.8 m h^{-1}) in our limited data. Calculated sediment yield rates from tests 1E, 2E, and 3E on PAM–treated channels with headcuts were 0.64, 6.15, and 5.18 kg min^{-1}, respectively, at flow rates of 0.0032, 0.0063, and 0.0063 (50, 100, and 100 gpm), respectively. The calculated sediment yield rates for tests 2E and 3E lie in the range of measured sediment yield rates from the untreated channels for the same flow rates, which is attributed to the lower controlling tail water elevation in tests 2E and 3E. These results show that PAM was effective in controlling erosion and headcut migration in an earthen channel under these experimental conditions.

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